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A Model of Black Cutworm (*Agrotis ipsilon*) Development

Description, Uses, and Implications

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ABSTRACT

A model describing black cutworm maturation based on thermal units calculated from weather station observations was developed and used to assess overwintering states and population ancestries and to determine when the eggs that produce corn-damaging larvae are laid. The results suggest that overwintering occurs at Ohio and Illinois latitudes in the pupal stage and also that migration may introduce populations into the region. Several population peaks occur each year, probably of two or more ancestries that are out of synchrony with each other. Based on the degree of success achieved in tracing blacklight catches, laboratory developmental rates approximate field development to within the precision of available data.

Simulations imply that the larvae damaging 34 cornfields in 1974 and 1975 developed from eggs laid not before October of the preceding year nor later than two weeks after planting, but most probably in the spring prior to planting. Subsequently, when degree-day accumulations were tabulated beginning in 1978 with the early spring moth catches, the model predicted damage would begin June 1; the first report of damage was received June 3.

This work provides a method for predicting the beginning of black cutworm problems in the Ohio-Illinois region, aiding farmers and pest management scouts in scheduling sampling activities. In addition, this research suggests appropriate seasonal timing for studying field characteristics that attract ovipositing females.

We are currently coupling the model to a model of corn crop development to evaluate potential losses with and without an emergency insecticide treatment, given an assessed larval population and age structure.

Keywords: Phenology, computer simulation, developmental rate, model, forecasting, overwintering, black cutworm, *Agrotis ipsilon*, blacklight trap, oviposition

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A Model of Black Cutworm (*Agrotis ipsilon*) Development: Description, Uses, and Implications

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CONTENTS

Urbana, Illinois March, 1982

Publications in the bulletin series report the results of investigations made or sponsored by the Experiment Station. The Illinois Agricultural Experiment Station provides equal opportunities in programs and employment.

Introduction and Objectives

Although the black cutworm (*Agrotis ipsilon*) causes economic loss on less than 10 percent of Illinois's corn acreage annually, it is a sporadic and unpredictable pest capable of destroying entire fields. The larvae damage several crop species by severing stalks at the base, thus killing the plants. Its life stages include the egg, six or more larval instars, the pupa, and the adult moth.

Even though the black cutworm is distributed throughout much of the Americas, Europe, Asia, and Africa, much remains unknown about this multivoltine pest. For example, does it overwinter as far north as Illinois, and if so, in what developmental stage(s)? Why are some fields damaged while similar neighboring fields are not? Sherrod, Shaw, and Luckmann (1979) associated tillage and agronomic factors with black cutworm damage, but how these factors affect the insect has not been established. Developmental rates in the laboratory vary with temperature, photoperiod, diet, and humidity, but development rates in the field have not been quantified.

In general terms, the purpose of our research is to prevent, or at least reduce, black cutworm losses while retaining profitable crop production. More specific research objectives and their interrelationships are shown in the objectives tree presented in Figures 1 and 2. Reading the objectives from top to bottom shows how the goals are to be realized; reading with the flow shows why specific tasks are needed.

Many of the objectives included in the tree have been addressed by previous research. Luckmann et al. (1976) (Objective A) determined the duration of black cutworm development for each life stage from oviposition to emergence under constant temperature conditions, and Goryshin and Akhmedov (1971) demonstrated the effects of photoperiod on larval developmental rates in the laboratory. Busching and Turpin (1977) determined developmental times (B) and survival (O) on several weed and crop diets. Broersma, Barrett, and Sillings (1976) and Odiyo (1975) provided information for Objective C, Broersma on flight and activity under varying temperatures and Odiyo on distribution and migration. Pautler et al. (1979) compared blacklight and virgin female trap catches (F). Reproductive calling behavior and oviposition rates were addressed by Swier, Rings, and Musick (1976, 1977) (Objectives F, H, and J). Busching and Turpin (1976) determined relative oviposition site preferences among many common weeds and crops (L). Larval sampling methods (N) were evaluated by Archer and Musick (1977a), as were feeding habits and cutting potential (Q) (1977b). Schoenbohm and Turpin (1977) addressed the effects of parasitism on consumption and cutting of

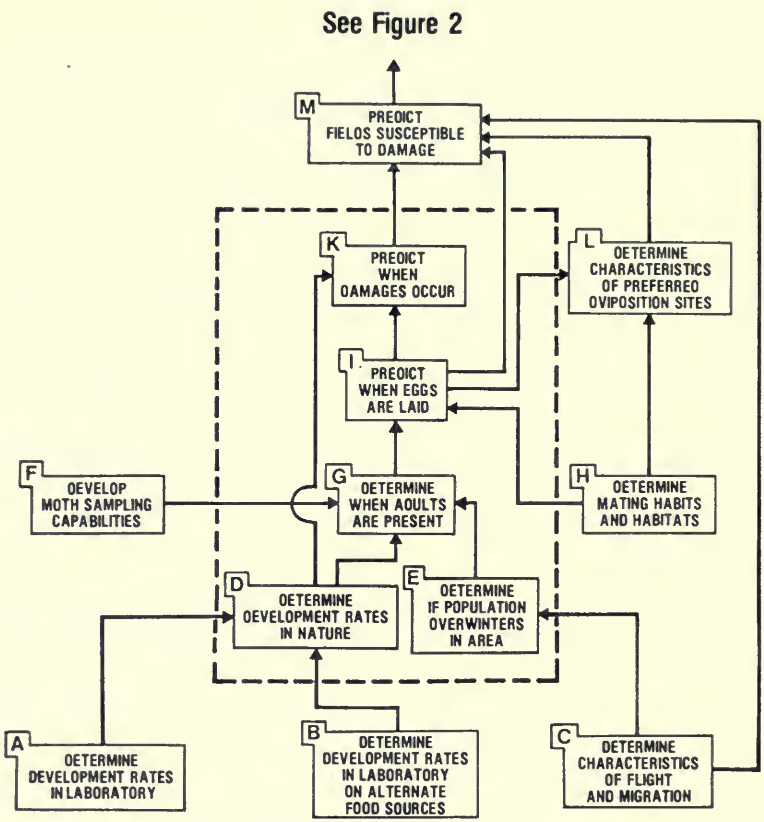

Figure 1. Objectives tree of applied black cutworm research: Part 1.

corn seedlings (Q), and early literature by Satterthwait (1933) considered consumption by each larval instar.

The objectives addressed by the work presented here are enclosed within the broken line box of Figure 1. Our primary objective was to develop an ability to predict when damage would occur in Illinois corn (Objective K). As depicted in Figure 1, attainment of this objective requires that we know developmental rates in the field (D) and when eggs are laid (I). We elected to develop a computer-based model for cutworm development following the biological reasoning presented in Sherrod et al. (1979). This model also proved useful for addressing the questions of when adults would be present (G) and whether the cutworm overwinters at these latitudes (E).

The precedent for using models in entomological research is well established. An important biological question can sometimes be addressed

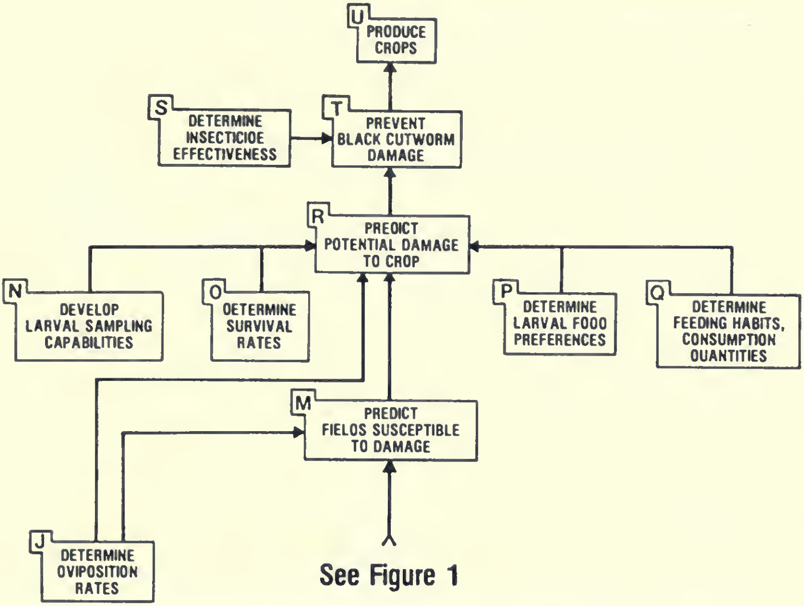

Figure 2. Objectives tree of applied black cutworm research: Part 2.

better with a model than by additional empirical investigation. Examples can be found in Tummala, Ruesink, and Haynes (1975), Stinner, Rabb, and Bradley (1974), Jones et al. (1977), and Gutierrez et al. (1977). Reports on models of corn insects include Loewer (1976) and Mooney and Turpin (1976).

Our procedure was to model black cutworm development as simply as possible and then compare the predictions of the model with field data. After a period of testing and several attempts to improve the model, we judged it sufficiently accurate for our purposes. The model is described in the following section, and its final evaluation and uses are described in the next three sections. The final section summarizes our conclusions and discusses potential future uses for the model. Computer code and documentation are included as an appendix.

Model Description

Certain assumptions were made about the influence of the environment on black cutworm development. Although many factors have some influence on developmental rate, only temperature was expected to have a significant effect on the median date of an event over areas as large as a typical cornfield. The following assumptions were made to allow a simple

formulation of the model and are implicit in its logic. Agreement between model predictions and empirical results supports the hypothesis that the effects of these assumptions are small:

1. The air temperature as recorded by a standard weather station can be used to calculate developmental rate without bias.
2. Extreme temperatures have no effect on rate of development beyond those accounted for by the simple degree-day concept.
3. The photoperiod effects are insignificant. When temperatures are near the threshold, developmental studies of other insects have shown that rates of development are actually slightly higher than a linear temperature dependent development equation would indicate (e.g., Guppy and Mukerji, 1974; Caffrey and Worthley, 1927), but these low temperatures are common only in early spring and fall, when the photoperiod may inhibit development (as inferred from Goryshin and Akhmedov, 1971). Consequently, these two effects tend to average out during critical periods; neither is likely to be a biasing factor during the winter aestivation or summer.
4. Field development is not significantly biased by typically occurring variations in humidity, soil moisture, or food quality and quantity nor by parasitism or predation.
5. Migrations into and out of the study area are not so great as to obscure peaks in population density.

The model determines probable dates for the life stage transitions of oviposition, egg hatch, molting, pupation, and adult emergence. Considering these transitions as events in the life history of the black cutworm, we term the model an "event simulator." Using the heat unit accumulations for median individuals as presented by Luckmann et al. (1976), the model can compute the dates for previous events, future events, or both, depending on whether the user's intent is to describe past events by running backwards in time or to predict the future by carrying the simulation forward in time. The threshold temperature of 10.4° C. suggested by Luckmann et al. (1976) was rounded to 10.5° C., and a sine wave interpolation technique based on daily high and low temperatures is used to estimate daily heat unit accumulation. Equations were modified from Allen (1976) to calculate heat-unit accumulations on a daily basis rather than on a half-day basis, with no maximum temperature cutoff. In addition to local daily weather observations, the model requires, as input, the date on which an initial developmental "event" occurred. This initial event is used as the starting point in computing dates for future or previous events.

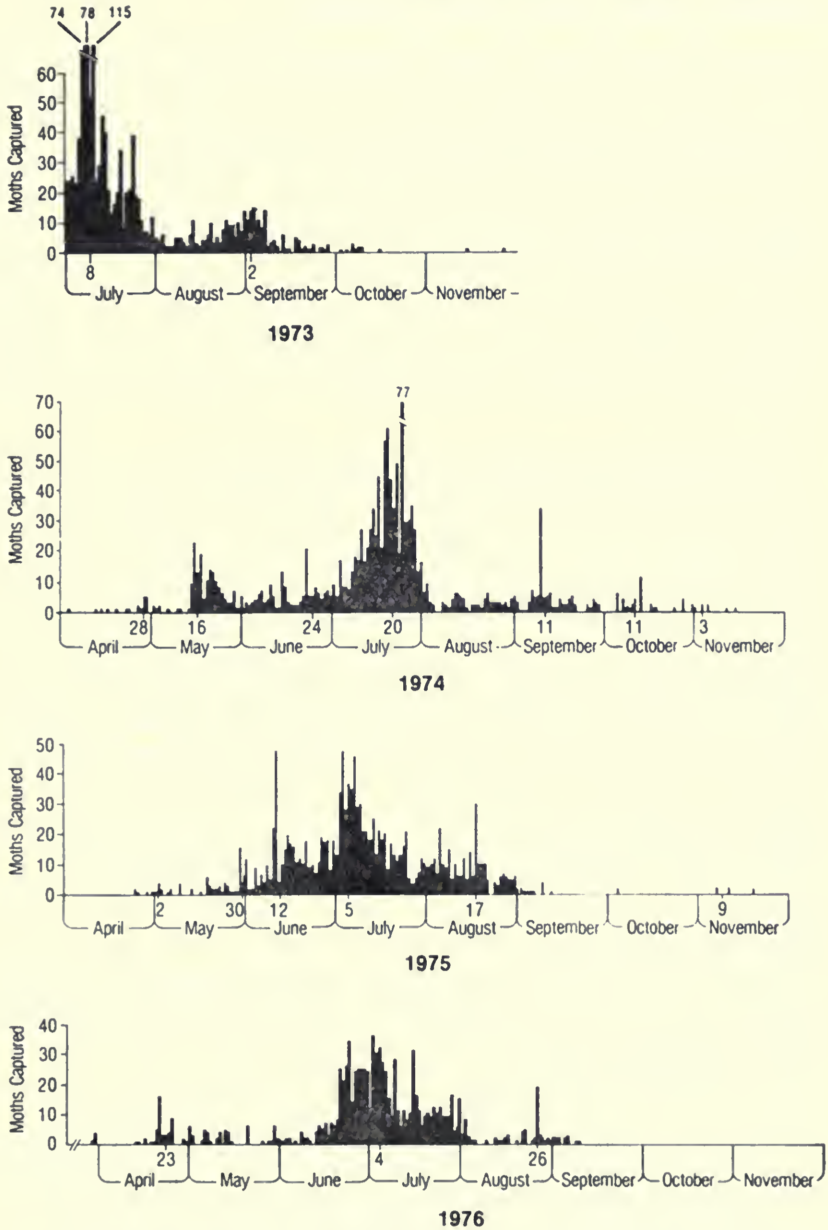

Figure 3. Daily blacklight trap catches of black cutworm moths from Wooster, Ohio, for the period beginning July 1973 and ending September 1976.

Analyses Based on Blacklight Trap Data

Three blacklight traps were operated near Wooster, Ohio, from July 1973 through September 1976, and catches were recorded daily (Figure 3). Since algorithms for interpreting black cutworm catches in light traps have not been developed and catch data interpretations are easily confounded because of deviant weather, population "peaks" were inferred using two methods: (1) subjective visual inspection after grouping into 10-day totals and (2) quantitative determination using 5-day running averages. The two methods produced similar results, although occasionally one would indicate a peak completely missed by the other. Typically, both would indicate a peak near a common date, usually within four days of each other. The peaks as determined by the two methods are indicated in Figure 4.

Comparing Model Predictions With the Data. Simulations were based on the 15 peaks obtained from the 10-day totals. They were used to evaluate the model as follows: (1) simulation proceeded in reverse time from specified dates of peak catch until oviposition, (2) simulated oviposition dates were compared to estimated peak catch dates, with differences within one week (model precision) interpreted as reliable, and (3) several reliable simulations (explaining most of the peaks) were required for model acceptance. In Figure 4 the X_n's represent the peaks estimated from 10-day trap accumulations, with the magnitude of these accumulations plotted on the ordinate. The Y_n's represent the simulated oviposition dates with subscripts corresponding to the peaks from which simulation began. For example, the observed flight of late April 1976 is labeled X_{14}, and the model reveals that eggs laid in mid-August 1975 (labeled Y_{14}) would produce a flight at the same time as X_{14}. Since the event Y_{14} occurs within a week of X_{11}, we conclude that the moths flying at X_{11} are the parents of those flying at X_{14}.

Following this procedure with all of the flights recorded by the light trap, we can obtain implications of the ancestors of most of these flights (Table 1). Although most of the flights can be traced to a logical parental flight, a few are more difficult.

- X_7, X_{12}, X_{13}: These "peaks" are of relatively low magnitude (Figures 3 and 4). The simulated oviposition dates (i.e., Y_7, Y_{12}, Y_{13}) coincide with periods of large flight activity, but not with flight peaks. The data do not suggest an easy explanation for these small peaks.
- X_{10}: No explanation is apparent other than, possibly, immigration.
- X_{15}: Although this large peak can best be explained by immigration, one alternative seems possible. The 5-day running average method

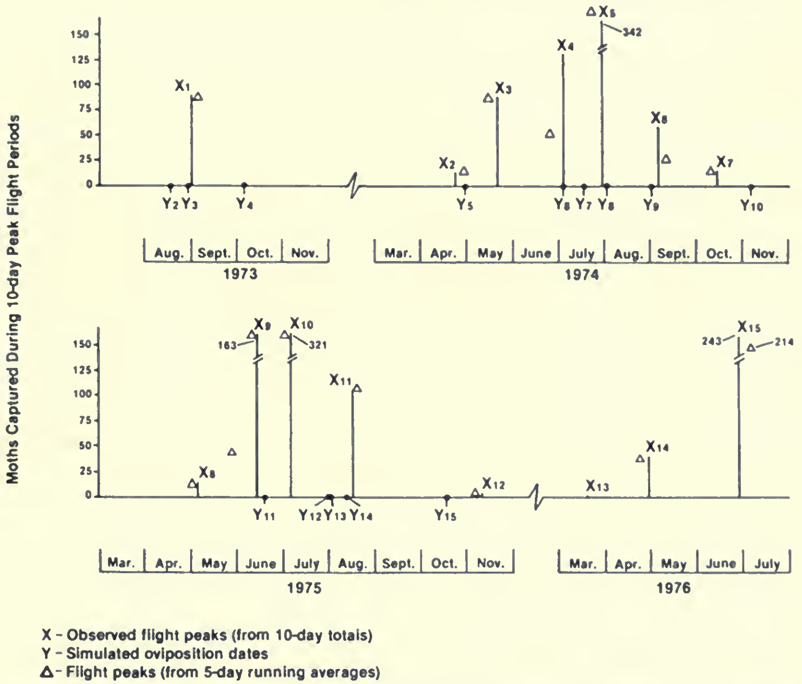

Figure 4. Simulated oviposition that produces observed blacklight trap peaks at Wooster, Ohio. The subscripts correlate the deposition dates of eggs that develop to produce observed adult populations.

suggests that the peak occurred seven days later than indicated by X_{15}, implying that oviposition and development were perhaps initiated by a late fall or early spring population.

Several alternative versions of the model were tested, but each failed to improve consistency; they were based on (1) developmental rate variation due to diet (data from Busching and Turpin, 1977), (2) lag time from female emergence to oviposition (data from Swier, Rings, and Musick, 1976), (3) development based on soil rather than air temperatures, and (4) development based on air (for eggs and instars 1 through 3) and soil (instars 4 through 7 and pupae) temperatures in combination. The factors considered in interpreting trap catches but not found useful in improving results included moon phase, precipitation, cold temperature, and wind.

One of our objectives (D in Figure 1) was to determine developmental rates in the field under natural conditions. Although the model is based on laboratory results, its predictions agree substantially with the light trap

Table 1. Simulation-Implied Black Cutworm Ancestries at Wooster, Ohio. Peaks of Generations Are Listed with Those of Hypothesized Progeny and Offspring. The X's Represent Moth Peaks from 1973 through Summer 1976.

Ancestry	Adult peaks
A1	X_1, X_3
A2	X_2, X_5, X_8
A3	X_4, X_6, X_9, X_{11}, X_{14}

data. We conclude that developmental rates in the fields are largely controlled by temperature and that daily maximum and minimum air temperatures as recorded by the U.S. Weather Bureau are as good as, or better than, any of the other temperature measurements we tested.

Overwintering. Black cutworm overwintering was addressed by noting the simulated life stages present on January 1 (Table 2). Five of the nine populations were found to overwinter as pupae. If one considers the slow development due to cold temperatures between the X_2 and X_3 dates and accepts them as fractions of the same population peaking near X_3, four of these five populations have coinciding dates of oviposition and ancestor peak (Figure 4: Y_3, Y_8, and Y_{14}). The other four displayed no agreement of alternative overwintering forms, and only the Y_9 oviposition date coincided with a detected moth flight. For this case, Figure 4 shows that a 5-day average specification of peaks would result in poor agreement of flight and simulated oviposition and more advanced development by January 1 than the 6th instar stage depicted in Table 2. The hypothesis that immigration can introduce some moths may explain the X_4, X_{10}, and X_{15} peaks. Analysis of spring 1978 pheromone trap data from Urbana, Illinois, also supports this hypothesis: weekly male capture rates increased with increasing weekly heat units to a point. When spring heat units accumulated to the point that all "typical" overwintering pupae had emerged, a sharp decline in catch occurred despite even higher weekly accumulations.

While neither these data nor this model can directly answer the question of whether overwintering occurs in the vicinity of Wooster, they suggest that some black cutworms do as pupae and that they are responsible for the small catch early in the spring. A larger catch in late June or early July may represent immigration. These results provide a tentative answer to Objective E and, together with the results for Objective D (see Figure 1) given in the previous section, help us meet Objective G.

Table 2. Simulated Oviposition That Produces Observed Adult Peaks and Simulated Overwintering States at Wooster, Ohio. Adult Peaks Were Estimated from 10-Day Totals. Those Estimated by 5-Day Running Averages Are Shown in Parentheses.

Adult peak	Simulated oviposition date	Developmental stage as of January 1	Peak emergence date	
X_2	8-17-73	pupae	4-22-74	(4-27-74)
X_3	8-27-73	pupae	5-18-74	(5-16-74)
X_4	10-03-73	2d instar	7-02-74	(6-24-74)
X_8	7-30-74	pupae	5-05-75	(5-02-75)
X_9	8-28-74	6th instar	6-16-75	(6-12-75)
X_{10}	11-04-74	eggs	7-07-75	(7-05-75)
X_{13}	8-02-75	pupae	3-22-76	
X_{14}	8-13-75	pupae	4-28-76	(4-23-76)
X_{15}	10-19-75	1st instar	6-27-76	(7-04-76)

Analyses Based on Corn-Damaging Larvae

During 1974 and 1975, black cutworm larvae found damaging corn in Illinois were collected and classified to instar (Sherrod, Shaw, and Luckmann, 1979). For each field from which larvae were collected, Sherrod completed a questionnaire recording the field's history, including pesticide applications and crops over the previous three years, planting dates and tillage practices, edaphic factors, and larval collection dates.

Assuming that (1) cutworms developed at the median rate, (2) the youngest field-collected larva had just molted, and (3) the oldest was just ready to molt, a range of feasible oviposition dates was determined by simulations based on these extreme events. The results of all simulations were compared with the recorded planting dates. Also, accumulative degree days between January 1 and simulated oviposition were calculated and compared. Sherrod's field observations and our corresponding simulation results are summarized in Table 3. The 1975 observations and results are probably more reliable than those of 1974, reflecting more extensive field sampling efforts.* The earliest and latest possible oviposition dates and the approximate thermal units accumulating from January 1 until these dates are shown in columns 3 through 6. The thermal units are not exact because the accumulations were calculated weekly. The field locations, larval collecting dates, instar determinations, planting dates, and approximate spring thermal unit deficiencies are also given in the table.

* D. W. Sherrod, 1979: personal communication.

Table 3. Simulated Egg Deposition Resulting in Larvae Damaging Various Illinois Cornfields and Approximate Centigrade Degree-Day Accumulations (CDD, base 10.5°) prior to Oviposition (field data from D. W. Sherrod).

County	Planting date	Earliest oviposition date	Latest oviposition date	CDD accumulating prior to oviposition: Most mature	CDD accumulating prior to oviposition: Least mature	CDD accumulating in fall (most mature larvae)	Sampling date	Number larvae recovered (by instar): 2d	3d	4th	5th	6th	7th
1974													
Scott	4-27					*	5-20			1	3	1	
Scott	4-25					*	5-29				1	3	
Hancock	4-25	3-26	4-14	39	69[a]		5-21				6		
Wayne	5-09	3-06	4-25	52	200		5-23				1	7	
Wayne	5-09	3-06	4-12	52	171		5-23					4	
Wayne	5-14	3-06	4-25	52	200		5-24				1	5	
Jersey	5-13	3-26	4-27	90	204		5-24				4	1	
Hancock	5-10					*	5-25					4	
Montgomery	5-05	4-09	5-04	118	232		5-30				1	4	
Shelby	5-07	3-04	4-24	26	165		5-30					2	3
Christian	5-10					*	5-31			1		2	1
St. Clair	5-20	4-11	5-15	162	357		6-03				2	3	1
St. Clair	5-20	4-22	5-15	236	357		6-03				4	2	
Champaign	4-29					*	6-06			4	7	11	1
Adams	5-24	4-20	5-22	188	382		6-10			1	2	3	1

Table 3. *Continued*

County	Planting date	Earliest oviposition date	Latest oviposition date	CDD accumulating prior to oviposition: Most mature	CDD accumulating prior to oviposition: Least mature	CDD accumulating in fall (most mature larvae)	Sampling date	Number larvae recovered (by instar): 2d	3d	4th	5th	6th	7th
........1975........													
Marion	4-15	11-18-74	4-29	[b]	115	10	5-13	1	4		1		
Adams	4-26	10-26-74	5-02	[c]	158	75	5-21			2	3	10	2
Iroquois	5-07	10-29-74	5-04	[b]	79	30	5-22		3	8	9		
Christian	5-10	10-30-74	5-05	[b]	139	25	5-24			2	6	5	
Jasper	5-18	10-26-74	5-05	[c]	152	65	5-27				5	6	1
Jasper	5-18	10-26-74	5-05	[c]	152	65	5-27				1	16	3
Jasper	5-18	10-26-74	5-16	[c]	194	65	5-27		1		2	8	1
Wabash	5-07	3-06	5-08	12	158[a]		5-28				6	4	3
Richland	5-16	3-20	5-09	27	218		5-28				8	5	6
Douglas	5-08	10-30-74	5-08	[b]	121	30	5-29				1	12	6
Richland	5-15	3-20	5-09	27	218		5-29				3	15	2
Richland	5-13	3-20	5-09	27	218		5-29				11	11	1
Richland	5-15	3-20	5-02	27	163		5-29					11	3
Richland	5-10	3-20	5-09	27	218		5-30				1	8	3
Richland	5-19	3-20	5-15	27	218		5-30			1	3	6	3
St. Clair	5-18	4-13	5-14	55	244		6-02				4	15	1
Piatt	5-14	11-08-74	5-16	[b]	192	5	5-30			5	6	11	5
St. Clair	5-18	4-13	5-18	55	244		6-02			2	4	5	7
Stephenson	6-02	10-26-74	5-24	[b]	151	40	6-16			4	16	1	3

* Computer run terminated because of lack of previous years' weather data (indicates fall oviposition).
[a] Six days' temperatures not included in this sum.
[b] Egg overwintering was simulated.
[c] First instar overwintering was simulated.

Possible oviposition dates ranged from the preceding October through late May, but many of the simulations confined oviposition to after early March. Simulations for 1974 terminated without results when the earliest possible oviposition date occurred in the preceding year because the weather file contained no pre-1974 data. However, those 1975 simulations that depicted fall oviposition indicate that, had only a few more degree-days accumulated in the spring (75 or less and, in most cases, 40 or less*), spring oviposition would have been indicated for even the most mature individuals.

One may expect oviposition to occur on only a few days within a simulation-determined range rather than on all or most days, with variation of individual development rates (Luckmann et al., 1976) being the primary mechanism producing the observed age structure. One would then expect that the most mature individuals are "fast" developers and the least mature "slow" rather than following the "median" development rate simulated. This theory suggests that the oviposition producing the damaging populations is reduced to an even narrower range than shown in Table 3. In view of our ultraconservative assumption that the most mature larva was just ready to transform, when perhaps it is more likely that it had just finished a transition, and vice versa for the least mature larva, all spring larvae could well have developed from spring oviposited eggs. Data in Luckmann et al. (1976) and Table 3 demonstrate that variation in developmental rates among individuals would account for the entire range of observed maturities in Table 3, even if all of the eggs were laid in the spring.

The 1975 simulations reveal that the most mature larvae typically could have developed from eggs deposited during the first 60 degree-days in spring. Most simulations also indicate that the least mature could *not* have been progeny of overwintering *larvae,* assuming median developmental rates (Luckmann et al., 1976). These facts suggest that the parents of the damaging population either migrate into Illinois in early spring or pass the winter in the vicinity as pupae. The exceptions are also in agreement with this conclusion if one allows for a four-day delay between female emergence and oviposition (Swier, Rings, and Musick, 1976).

The simulated oviposition date resulting in the least mature larva was generally a few days before planting (Table 3), which is consistent with the hypothesis (Sherrod, Shaw, and Luckmann, 1979) that weedy fields tilled shortly before planting are suspect of damage. This trend was especially clear in the more extensively sampled 1975 fields but also reflected

* Degree-days are expressed in degrees centigrade.

in the last few fields observed in 1974. In problem fields observed early in 1974, the latest possible oviposition date was simulated as two weeks to one month prior to planting. But the less intensive field collecting effort in 1974 resulted in few of the hard-to-find small instar larvae being captured; younger larvae than those found could have been present. Thus, the latest feasible oviposition dates may fall later in 1974 and nearer planting than indicated.

Generalizing our findings, the eggs producing the economically important cohorts are not laid before late fall nor later than May (as late as two weeks after planting), but typically after the first 30 spring degree-days accumulate and before planting. Consequently, simulations suggest that moths emerge from overwintering pupae (or possibly migrate into Illinois) in early spring, locate attractive sites for oviposition, and then lay eggs that develop into the larvae that damage corn. This result contributes to Objective I (Figure 1).

Pheromone Trap Catch as Indicator of Larval Development and Damage

The purpose of the efforts described here was to further test the hypothesis that the larvae damaging Illinois cornfields develop from spring-deposited eggs. This testing was accomplished in 1978 by sampling larvae, projecting previous oviposition, and comparing with adult catches. Pheromone traps were operated at Collinsville and Urbana, and field sampling for larvae included sweepnet, pyrethrin drenches, and examination of the soil around damaged plants. Heat-unit accumulations were secured once or more per week during spring and summer from the National Weather Service, Lafayette, Indiana, for several Illinois locations.

Weekly spring surveillance of a field near Belleville yielded larvae on two dates: a single 2d instar larva was found on April 18; on May 17, four 4th, three 5th, and two 6th instar larvae were located. Assuming the larva observed on April 18 was approximately in the midst of its 2d instar and a "median" developer, this cutworm would have originated from an egg laid between March 29 and April 5. The age distribution of the larvae captured on May 17 suggests that the median larva molted to a 5th instar at about this time. Area weather records reveal that a median developing cutworm undergoing the 4th molt around May 17 would also have hatched from eggs laid after March 29 and before April 5. In a pheromone trap about 10 miles north of this field, moth catch increased dramatically from near zero levels during this same time (Table 4).

Table 4. Pheromone Trap Catches, Collinsville, Illinois, 1978.

Date checked	Moths captured
3-24	2
3-28	0
4-06	10
4-12	14
4-20	23
4-30	3

Table 5. Cutworms Captured June 13, 1978, in a Cornfield in Hancock County, Illinois.

Instar	Number observed	Percent
3	4	13
4	5	17
5	9	30
6	10	33
7	2	7
	Total 30	

Larvae collected from a field in Hancock County on June 13 were classified by instar, and the results are summarized in Table 5. The predominant event appears to be the 5th molt, which we assume occurred for the average cohort the evening of June 12. Using degree-day accumulations for Quincy, Illinois, peak oviposition was projected about the evening of May 21. Although adult trap data are not available for Hancock County, it is located on about the same latitude as Urbana; the Urbana moth catches (Figure 5) indicate a large peak at that time.

Larvae of instars 3 through 7 were present in this Hancock County field on June 13 (Table 5). The predominant transition at this time, the 5th molt, requires about 261 degree-days for the median individual (Luckmann et al., 1976). A small number, 7 percent, had attained the 7th instar by June 13; this group probably represents the fast-developing portion of the population that may reach this maturity in as few as 261 degree-days. Thirteen percent of the sampled individuals were in the 3d instar of development, perhaps representing the slow-maturing portion of the population. Slow-maturing individuals may need as many as 275 degree-days to reach the 4th instar. Consequently, all larvae represented in Table 5 could have developed from eggs laid the same evening.

To test more directly our ability to meet Objective K (Figure 1), weather records from Decatur, Illinois, were used to project the date of 5th molt, assuming that oviposition initiated with the earliest nontrivial moth catch in the Urbana pheromone trap (Figure 5). Based on data

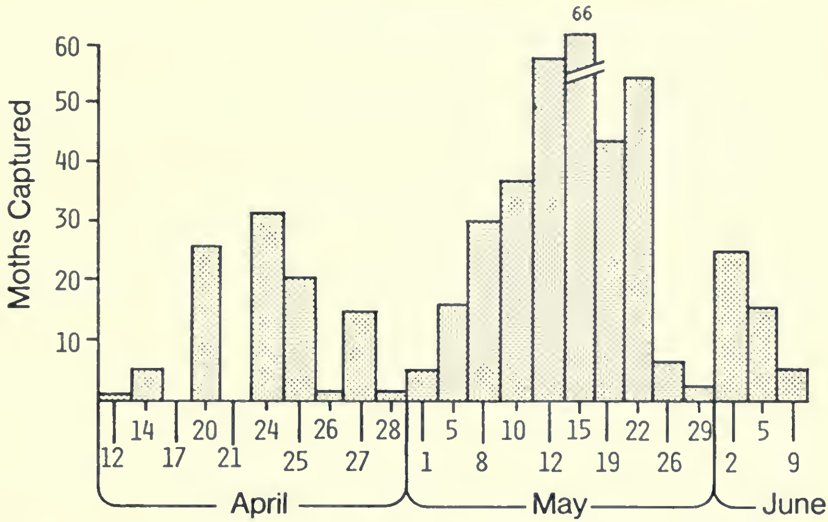

Figure 5. Black cutworm pheromone trap catches at Urbana, Illinois, spring 1978. The dates on which the trap was checked are indicated numerically.

received from the National Weather Service on June 1, 1978, the model indicated that the most mature individuals should be reaching the 6th instar and damage should soon begin in the Decatur-Urbana area. Extension entomologists later reported that the first field in the vicinity was sprayed on June 3, just two days later. Subsequent field sampling on June 5 indicated that 6th instar larvae were present, but no 7th instars were found.

Conclusions and Future Uses

The model described in this paper has demonstrated an ability to trace cutworm populations with fidelity. It has been evaluated using light trap data for adults and using larval age distributions in conjunction with pheromone trap data.

Simulations using data from central and southern Illinois and from central Ohio yield the following conclusions:

1. Larvae that damage corn have not passed the winter, but instead come from eggs laid in the spring, usually before corn is planted.
2. In any one year there are two or more cutworm ancestries present simultaneously. In general, the moths taken during a peak flight are not the progeny of the immediately preceding peak, but rather of an earlier peak.

3. The earliest spring flight(s) appear(s) to be an overwintering population, one that passed the winter in the pupal stage. Overwintering in other stages occurs rarely or not at all.
4. A large flight often occurs in late June. The simplest explanation for this flight is massive immigration.
5. Adults present in mid- to late summer lay eggs that develop to the pupal stage by fall, with adults emerging the following spring.

It should be stated that although this study strongly supports the above conclusions, no model can prove such statements. Biological investigation is needed to substantiate or refute model implications.

This relatively simple model could be modified to improve its realism and reduce the number of assumptions mentioned on page 8. For the purposes of Objective K (Figure 1), however, such modification is not advisable. Instead, the logical next phase of our research is to progress to Objectives M and R. At the same time, effort should begin to make use of our existing capability to forecast the date of first damage.

The model is being used in Illinois to time research and management activities. The findings presented here will be used in observing fields between early spring and planting to study field characteristics that make a field attractive for oviposition (Objective L). The objective is to state which field characteristics over the specified period prompt substantial oviposition. Spring adult trap catches are used to initialize the model and, based on weather predictions, project when black cutworm problems will begin in regions throughout the state (K). Pest management and extension scouting activities may be scheduled accordingly.

In addition to the work reported here, we have coupled the model to a simple model of plant development to evaluate potential damage versus larval maturity (R). Once a reliable population assessment capability has been developed, damages with and without an insecticide treatment can be evaluated concurrently. The resulting information may help establish accurate economic thresholds as functions of larval maturity, plant development, and environmental conditions. If the characteristics conducive to spring oviposition can be determined well enough to identify susceptible fields, a coupled plant and insect model may be used to ascribe a range of planting dates such that the crop would not be subject to damage (Objective M).

In conclusion, our ultimate goal is to state that if one can (1) avoid specific, critically timed field characteristics by cultural practices *or* (2) time planting, weather permitting, so that the crop is not susceptible to damage when the larvae are most destructive, then black cutworm damage can be avoided (Objective T).

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APPENDIX

Contents

Computer Specifications and Data Base

The model was executed using a Control Data Corporation Cyber (170 series, model 172) computer. The program was written in Fortran IV as subroutines to facilitate manipulation and verification.

Illinois daily weather observations for 1974 and 1975 were obtained from the National Oceanic and Atmospheric Administration (NOAA). These data were recorded on magnetic tape in NOAA's 486 format and follow in ascending order of station and date.

Weather observations from Wooster, Ohio, including soil temperatures, were keypunched. Plots of the air temperatures were created using a Calcomp pen plotter.

Since the model is executed using only a small number of simple subroutines, the computer code is straightforward and readily adaptable. If other phenomena can be adequately described by degree-days, they may be modeled simply by changing a few computer statements in this program. Print statements and limits on pointers will need to be changed. The threshold temperature can be changed by changing one parameter, and the number of degree-days required by the program for the various stages can be altered by substituting values in a table. This table may easily be expanded or contracted for modeling differing numbers of events.

The computer program (EVENT5) was written in subroutines to enhance modification and verification. Subroutines handle tasks of calculating calendar dates, estimating degree-days, locating weather stations on file, printing results, adjusting pointers, and building a table that indicates event dates. Small computer programs testing each of the subroutines have demonstrated that all subroutines are accurate, and the brief main program has been verified by comparing simulation results to those of a simpler, less general, but more explicit version.

Program and Subroutine Documentation

EVENT5

Purpose: Based on observations at a sampling date and degree-day accumulations, to describe black cutworm development at a particular location

Program Language: Fortran IV

Tape Input: Modified National Oceanic and Atmospheric weather tape record 486. Tape is referenced as "WEATHR."

Card Input:

Card 1: Columns 1–4 Station identifier
5 blank
6–11 date (year, month, day)

Card 2: Columns 1–2 number of event indicators (up to 10); (see p. 26)
3 blank
4–5 event indicator
6 blank
7–8 event indicator
9 blank
.
.
.

Card 3: Column 1 enter "1" if another simulation
"0" otherwise

Cards 4, 5, 6, etc., as cards 1, 2, 3 if more simulations indicated

Output:

1. Weekly degree-day accumulations from January 1
2. Table of oviposition, hatch, molt, pupation, and emergence dates for all sampling date age groups specified, both prior to and after the observation date

Routines used: CALDAT, WETHR, OPENER, WRITER, EVENT, FWDTBL

Mechanics: Weather tape is rewound, routine OPENER called to identify and locate station and to find first date for which degree-days are to be calculated, advancing weather tape appropriately. Table DDTBL is then built, using routine WETHR to calculate daily sine wave approximated centigrade degree-days (10.5° base). Parameter "I" is used to store the integer indicator of the sampling date and is not changed after this figure is determined. For each sampling date age group, the relative timing of events is determined and stored, using routine EVENT and Table IVTTBL. This relative timing of events is stored as integers indicating number of days elapsed since a reference time. (These integers are later converted to Julien dates and printed.) After Table IVTTBL is built for events occurring prior to the sampling time, degree-days from January 1 until the oviposition date are printed weekly, using routine CALDAT to calculate dates. Table DDTBL is built afresh, reading more weather data from the tape. Then, routine FWDTBL is called to determine the elapsed time (in days) for future events. Next, IVTTBL is completed. Routine WRITER is then called to print the dates of all calculated developmental events (again using CALDAT to calculate dates). A card

is then read to determine if more simulations are to be run; if yes, the process repeats.

Event Indicators:

01 oviposition
02 hatch
03 1st molt
04 2d molt
05 3d molt
06 4th molt
07 5th molt
08 6th molt
09 pupation
10 emergence

Subroutine: CALDAT (IMONTH, IDAY, IYEAR, ILEAP, IDAYTL)

Purpose: To calculate the calendar date given the day of the year. The routine handles days past 365 or 366 and days less than 1 by adjusting the year; consequently, the Julien date can be calculated correctly for any positive or negative whole number.

Required Input:

IDAYTL — day of year
IYEAR — reference year
ILEAP — leap year indicator ("1" if no, "2" if yes)

Output:

IMONTH — Julien month
IDAY — Julien day
IYEAR — year
ILEAP — leap year indicator
IDAYTL — day of year (in IYEAR)

Additional Constraints: A 13-column by 2-row table must be included in the calling program in labelled COMMN1; this table, ITBLDA, contains the following integers:

0 31 59 90 120 151 181 212 243 273 304 334 365
0 31 60 91 121 152 182 213 244 274 305 335 366.

Subroutine: WETHR (THIGH, TLOW, TACCUM, THRS)

Purpose: To calculate *centigrade* degree-days using a sine wave interpolation from daily high and low *Fahrenheit* temperatures. Degree-days are

calculated on a daily basis and returned to the calling program. The threshold temperature is supplied by the user; no cutoff temperature is employed.

Required Input:
THIGH — daily high Fahrenheit temperature
TLOW — daily low Fahrenheit temperature
THRS — threshold temperature (in Fahrenheit)

Output: TACCUM — daily centigrade degree-day total

Subroutine: OPENER, RETURNS (M1)

Purpose: To locate a logical record on a sequential tape (sorted in ascending order by weather station (primary) and date (YYMMDD), as identified by card input and incremented by −250. The first logical record of the station is identified if less than 250 station records precede the specified date.

Required Input:
ISTN — four-character numeric code identifying the weather station
IYEAR — reference year
IMONTH — month
IDAY — day
Input is read in the above order from card input in the format:
(I4,X,3I2)

Output:

1. The input variables and a leap year indicator (ILEAP, which is set to "1" if no or "2" if yes) are initialized and stored in labelled common COMMN3.
2. From the sequential tape and stored in labelled common COMMN4:
   NSTN — four-character numeric code identifying the weather station
   NSEQ — six characters pertaining to date (YYMMDD)
   MAX — daily high Fahrenheit temperature
   MIN — daily low Fahrenheit temperature

Additional Constraints:

1. Labelled common COMMN1 must be included in the calling program, containing the table ITBLDA (13,2):
   0 31 59 90 120 151 181 212 243 273 304 334 365
   0 31 60 91 121 152 182 213 244 274 305 335 366.
2. Special return M1 is used when the specified station cannot be located on the sequential tape.

Subroutine: **WRITER (NREFYR, NREFLP, NREF, KEND)**

Purpose: To print the dates of simulated events; up to 10 events for each of up to 10 different groups

Required Input:

NREFYR — The reference year

NREFLP — Leap year indicator ("1" if no, "2" if yes)

NREF — Reference day of year minus 1 (NREF = 0 for January 1)

KEND — Number of event dates to be printed per group

From Labelled Common COMMN5:

ISGKEY — Number of different groups whose events are to be printed

IDVGRP(J) — Development groups ("1" — just oviposited — to "10" — just emerged). Note: J ranges from 1 to ISGKEY; dimensioned 10.

IVTTBL(I,J) — Table showing number of days from reference day from which group I experienced event J; dimensioned 10 x 10

Output: The group and dates of events are printed along with headings.

Additional Constraints: Subroutine CALDAT is referenced, and consequently, labelled common COMMN1 with table ITBLDA(13,2) is required; see routine CALDAT documentation for more information.

Subroutine: **EVENT (STAGE, ISTAGE, INT1), RETURNS(M1)**

Purpose: To adjust indicators after a change of state (i.e., pupation, molt, emergence, etc.). The adjusted indicators are the event (1 through 10) and the requirement for another event to occur. This routine may progress either forward or backward in time. Control passes to the special return location when boundary events occur.

Required Input:

ISTAGE — Pointer indicating which event occurred last (1-10)

INT1 — Forward-reverse time indicator (−1 if reverse, +1 if forward)

Output:

ISTAGE — Pointer indicating which event will occur next (1-10)

STAGE — Indicator of the next event thermal unit requirements

Additional Constraints:

1. A 10-element vector (STGTBL) must be contained in labelled common (COMMN2) in the calling program; each element must contain the requirement for the i^{th} event.
2. After the boundary events have occurred, location ISTAGE will contain an inappropriate number and will need to be reset before using the location again.

Subroutine: FWDTBL (I,LIMIT)

Purpose: To predict the number of days elapsing since a reference date when future events will occur (up to 10 different observed groups)

Required Input:

1. I — offset; used to adjust elapsed time from reference day. This time will be 0 if 1st day's weather immediately follows reference day.
   LIMIT — Indicator showing the number of elements in table DDTBL (daily degree-days); maximum is 250.
2. From labelled common COMMN5:
   ISGKEY — The number of observed groups whose events are to be calculated
   IDVGRP — Development groups; "1" (just oviposited) to "10" (emerged). Dimensioned 10.
3. From labelled common COMMN6:
   DDTBL — 250 element vector of daily degree-days. Not all elements need be filled.
4. From labelled common COMMN2:
   STGTBL — 10-element vector specifying degree-day requirements of events

Output: IVTTBL — A 10-column by 10-row table showing the number of days from reference day for which events occur for observed groups. All postobservation date events are determined in subroutine FWDTBL. Groups are distinguished by rows, events by columns. Table follows ISGKEY and IDVGRP in labelled common COMMN5.

Additional Constraints: Subroutine EVENT is called with INT1 Initialized 1 (indicating forward time). See routine EVENT documentation for more information.

Computer Code

```
      PROGRAM EVENT5(INPUT,OUTPUT,WEATHR,TAPE7=WEATHR,TAPE5=INPUT,
     XTAPE6=OUTPUT)
      COMMON/COMMN6/DDTBL(250)
      COMMON/COMMN1/ITBLDA(13,2)
      COMMON/COMMN2/STGTBL(10)
      COMMON/COMMN3/ISTN,IYEAR,IMONTH,IDAY,ILEAP
      COMMON/COMMN4/NSTN,NSEQ,TMAX,TMIN
      COMMON/COMMN5/ISGKEY,IDVGRP(10),IVTTBL(10,10)
      DATA ITBLDA/0,31,59,90,120,151,181,212,243,273,304,334,365,0,
     X31,60,91,121,152,182,213,244,274,305,335,366/
      DATA STGTBL/0.,52.,99.,134.,170.,208.,261.,346.,405.,643./
 5    REWIND 7
      CALL OPENER,RETURNS(100)
      I=1
      ISEQ=10000*IYEAR+100*IMONTH+IDAY
 10   CALL WETHR(TMAX,TMIN,DDTBL(I),50.9)
      IF(NSEQ.GE.ISEQ) GO TO 20
      READ(7,810)NSTN,NSEQ,TMAX,TMIN
      I=I+1
      GO TO 10
 20   WRITE(6,910)
      READ(5,820)ISGKEY,(IDVGRP(J),J=1,10)
      DO 60 J=1,ISGKEY
          II=I
          ISTAGE=IDVGRP(J)
          STAGE=STGTBL(ISTAGE)
          DGDAY=STAGE
 50       IF(DGDAY.GT.STAGE) GO TO 55
              IVTTBL(J,ISTAGE)=II
              CALL EVENT(STAGE,ISTAGE,-1),RETURNS(60)
 55       DGDAY=DGDAY-DDTBL(II)
          II=II-1
          IF(II.GT.0) GO TO 50
              WRITE(6,915)
 915  FORMAT(" LIMITS OF TABLE EXCEEDED WITHOUT SATISFYING DD  ",
     X"REQUIREMENTS")
      GO TO 100
 820  FORMAT(11(I2,1X))
 910  FORMAT(" ENTER NUMBER OF DEVELOPMENTAL GROUPS AND GROUP INDICAT",
     X"ORS")
 60       CONTINUE
      IDAYTL=ITBLDA(IMONTH,ILEAP)+IDAY
      IJAN1=I-IDAYTL+1
      IREF=IJAN1-1
      IF(IJAN1.LT.1) GO TO 95
      IF(IJAN1.GT.IVTTBL(1,1))GO TO 95
          DGDAY=0.
          NYEAR=IYEAR
          NLEAP=ILEAP
          IEND=IVTTBL(I,1)
          DO 90 IDAYTL=IJAN1,IEND
 80           DGDAY=DGDAY+DDTBL(IDAYTL)
          IF(IDAYTL/7*7.NE.IDAYTL)GO TO 90
          NDAYTL=IDAYTL-IREF
          CALL CALDAT(NMONTH,NDAY,NYEAR,NLEAP,NDAYTL)
          WRITE(6,920)DGDAY,NMONTH,NDAY,NYEAR
 90   CONTINUE
C     BUILD DDTBL FOR FORWARD DIRECTION
   95 CONTINUE
      II=0
  125 READ(7,810) NSTN,NSEQ,TMAX,TMIN
      IF (EOF(7).NE.0) GO TO 115
      IF (NSTN.NE.ISTN) GO TO 120
      II=II+1
      IF(II.GT.250) GO TO 121
      CALL WETHR(TMAX,TMIN,DDTBL(II),50.9)
      GO TO 125
C     FWD IVTTBL
  121 II=250
  120 CALL FWDTBL(I.II)
```

```
C      PRINT IVTTBL(10,10)
       CALL WRITER(IYEAR,ILEAP,IREF,10)
 100   WRITE(6,950)
 950   FORMAT(" RUN COMPLETE.  IF MORE RUNS DESIRED, TYPE '1'")
       READ(5,830)IREPLY
       IF(IREPLY.EQ.1) GO TO 5
 830   FORMAT(I1)
       STOP
  115  WRITE(6,150)
  150  FORMAT(//,5X,*UNEXPECTED EOF IN WEATHER TAPE*)
       STOP
 810   FORMAT(2X,I4,I6,1X,2F3.0)
 920   FORMAT(" ",F4.0," CDD ACCUMULATED FROM 1-01 TO ",I2,"-",I2,"-",I2)
       END
```

```
       SUBROUTINE WETHR(THIGH,TLOW,TACCUM,THRS)
        IF (THIGH.GT.THRS) GOTO 13
            TACCUM=0.0
            RETURN
 13     TAVG = (TLOW+THIGH)*0.5
        IF (TLOW.LT.THRS) GOTO 23
            TACCUM=TAVG-THRS
            GO TO 30
 23     THETA = ASIN((THRS-TAVG)/(THIGH-TAVG))
        DUM1 = (TAVG-THRS)*((3.14159/2)-THETA)
        DUM2 = (THIGH-TAVG)*COS(THETA)
        TACCUM = (DUM1 + DUM2)/3.14159
 30    CONTINUE
       TACCUM=TACCUM*5./9.
 33     RETURN
       END
```

```
       SUBROUTINE OPENER,RETURNS(M1)
       COMMON/COMMN1/ITBLDA(13,2)
       COMMON/COMMN3/ISTN,IYEAR,IMONTH,IDAY,ILEAP
       COMMON/COMMN4/NSTN,NSEQ,TMAX,TMIN
       READ (5,800) ISTN,IYEAR,IMONTH,IDAY
       WRITE(6,905)ISTN,IMONTH,IDAY,IYEAR
 905   FORMAT(" STATION ",I4,4X,I2,"-",I2,"-",I2)
       ILEAP=1
       IF(IYEAR/4*4.EQ.IYEAR)ILEAP=2
       IDAY1=(IYEAR-70)*365+ITBLDA(IMONTH,ILEAP)+IDAY-248
       IYR1=70
       ILP1=1
       CALL CALDAT(IMO1,IDA1,IYR1,ILP1,IDAY1)
       ISEQ1=10000*IYR1+100*IMO1+IDA1
 50    READ(7,810)NSTN,NSEQ,TMAX,TMIN
       IF (EOF(7).NE.0) GO TO 960
           IF(NSTN.LT.ISTN) GO TO 50
       IF(NSTN.EQ.ISTN) GO TO 55
           WRITE(6,900)ISTN
           RETURN M1
 55    IF(NSEQ.GE.ISEQ1) RETURN
           READ(7,810)NSTN,NSEQ,TMAX,TMIN
           GO TO 55
 800   FORMAT(I4,X,3I2)
 810   FORMAT(2X,I4,I6,1X,2F3.0)
 900   FORMAT(" STATION ",I4," NOT FOUND")
  960  WRITE(6,970)
  970  FORMAT(//,*   EOF WETHR  *)
       STOP
       END
```

```
      SUBROUTINE WRITER(NREFYR,NREFLP,NREF,KEND)
      DIMENSION NYRTBL(10),NMOTBL(10),NDATBL(10)
      COMMON/COMMN1/ITBLDA(13,2)
      COMMON/COMMN5/ISGKEY,IDVGRP(10),IVTTBL(10,10)
      WRITE(6,915)
  915 FORMAT(1H1,//)
      WRITE(6,920)
 920  FORMAT("  BCW    OVIPO-    HATCH     1ST      2ND      3RD    ",
     X"  4TH      ",
     X"  5TH      6TH     PUPA-    EMER- ",/,
     X" ",
     X"GROUP   SITION             MOLT     MOLT     MOLT     MOLT    ",
     X" MOLT     MOLT     TION     GENCE "/)
      DO 20 J=1,ISGKEY
          DO 10 K=1,KEND
          NYEAR=NREFYR
          NLEAP=NREFLP
          NDAYS=IVTTBL(J,K)-NREF
          CALL CALDAT(NMONTH,NDAY,NYEAR,NLEAP,NDAYS)
          NMOTBL(K)=NMONTH
          NDATBL(K)=NDAY
          NYRTBL(K)=NYEAR
 10       CONTINUE
      WRITE(6,930)IDVGRP(J),((NMOTBL(K),NDATBL(K),NYRTBL(K)),K=1,
     XKEND)
 930  FORMAT(" ",I2,6X,10(I2,"-",I2,"-",I2,1X))
 20   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE EVENT(STAGE,ISTAGE,INT1),RETURNS(M1)
      COMMON/COMMN2/STGTBL(10)
      ISTAGE=ISTAGE+INT1
      IF(ISTAGE.GT.10) RETURN M1
      IF(ISTAGE.LT.1) RETURN M1
      STAGE=STGTBL(ISTAGE)
      RETURN
      END
```

```
      SUBROUTINE CALDAT(IMONTH,IDAY,IYEAR,ILEAP,IDAYTL)
      COMMON/COMMN1/ITBLDA(13,2)
 87   INT1=1
      INT2=ITBLDA(13,ILEAP)
      IF(IDAYTL.GT.INT2) GO TO 90
      IF(IDAYTL.GT.0) GO TO 97
      INT1=-1
      IF(ILEAP.EQ.2)INT2=365
      IF((IYEAR-1)/4*4.EQ.IYEAR-1)INT2=366
 90   IYEAR=IYEAR+INT1
      IDAYTL=IDAYTL-INT1*INT2
      ILEAP=1
      IF(IYEAR/4*4.EQ.IYEAR) ILEAP=2
      GO TO 87
 97   DO 107 K=1,12
 107  IF(IDAYTL.GT.ITBLDA(K,ILEAP))IMONTH=K
      IDAY=IDAYTL-ITBLDA(IMONTH,ILEAP)
      RETURN
      END
```

```
      SUBROUTINE FWDTBL(I,LIMIT)
      COMMON/COMMN6/DDTBL(250)
      COMMON/COMMN5/ISGKEY,IDVGRP(10),IVTTBL(10,10)
      COMMON/COMMN2/STGTBL(10)
      DO 60 J=1,ISGKEY
      II=1
      ISTAGE=IDVGRP(J)
      IF (ISTAGE.LT.10) GO TO 40
      WRITE(6,3) ISTAGE
    3 FORMAT(/,5X,*SUBRTN FWDTBL: ISTAGE TOO BIG*,  I10)
      STOP
   40 CONTINUE
      DGDAY=STGTBL(ISTAGE)
      ISTAGE=ISTAGE+1
      STAGE=STGTBL(ISTAGE)
   50 DGDAY=DGDAY+DDTBL(II)
      IF (DGDAY .LT.STAGE) GO TO 55
      IVTTBL(J,ISTAGE)=II+I
      CALL EVENT(STAGE,ISTAGE,1), RETURNS(60)
   55 II=II+1
   56 IF (II.LE.LIMIT) GO TO 50
      WRITE(6,1)
    1 FORMAT(//,5X,*TABLE LIMIT FOR DDTBL EXCEEDED *)
      STOP
   60 CONTINUE
      RETURN
      END
```

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